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**MAGNETIC DEPOPULATION OF SUBBANDS
AND UNIVERSAL CONDUCTANCE FLUCTUATIONS
IN QUASI-ONE DIMENSIONAL GaAs-AlGaAs HETEROSTRUCTURES**

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Narrow conducting channels have been fabricated in the two dimensional electron gas in a GaAs-AlGaAs heterostructure, using a recently developed shallow mesa etch technique. Four terminal high field magnetoresistance measurements at temperatures down to 2 K have been performed on samples with etched width between 8 μm and 0.5 μm . The Shubnikov-de Haas oscillations are studied, and clear evidence is presented for magnetic depopulation of 1-dimensional subbands. The data for the 0.5 μm wide channel are in satisfactory agreement with a simple analysis based on a parabolic confinement potential. Large sidewall depletion effects are found, in agreement with our recent analysis of the weak field negative magnetoresistance. We also observe irregular structure in the magnetoresistance. The dependence of the effects on the orientation of the magnetic field shows that the magnetoresistance arises from the orbital motion of the 2-dimensional electrons. The magnitude and typical field scales of the aperiodic structure are in agreement with predictions based on the theory of universal conductance fluctuations.

The study of low temperature transport properties of a laterally confined 2-dimensional electron gas (2-DEG) in narrow GaAs-AlGaAs heterostructures was (as in the case of narrow channel Si-MOSFETs) originally motivated by an interest in one-dimensional localization and electron interaction effects^{1,3} and a search for clear manifestations of the quantum size effect (QSE)⁴. The QSE is thought to give rise to regular structure in the channel resistance if the Fermi level is tuned past the density of states peaks associated with the 1-dimensional subbands. This could be observed by varying the electron density (by means of a gate voltage) or by modifying the subband structure (by means of a magnetic field), in the regime of electric or magnetic depopulation of subbands^{5,7}. However, since the advent of the theories by Lee and Stone⁸, and Altshuler and Khmel'nitskii⁹ on universal conductance fluctuations (UCF), it is known that part of the aperiodic but reproducible oscillations in the conductance as a function of gate voltage or magnetic field usually observed in these systems has to be attributed to the latter phenomenon, rather than to the QSE.

We have measured weak and high field four terminal magnetoresistance in narrow conducting chan-

nels in GaAs-AlGaAs heterostructures. In this paper high field data are presented. The sample fabrication¹⁰ and the weak field data¹¹ are discussed elsewhere. Oscillatory structure in the magnetoresistance is shown to arise from both subband depopulation effects and universal conductance fluctuations. Both effects are a consequence of the orbital motion of the electrons in the plane of the original 2-dimensional electron gas (the UCF arise from quantum interference of the conduction electrons in the random impurity potential in sufficiently small samples). We also measured the field orientation dependence of the magnetoresistance, and show that the observed effects are indeed a consequence of this 2-dimensional orbital motion.

The samples have been fabricated using a shallow mesa-etch technique¹⁰. GaAs-AlGaAs heterostructure material grown by Metal-Organic Chemical Vapor Deposition was used. The 2-DEG at the GaAs-AlGaAs interface in this material has at low temperatures a mobility of 10 m²/Vs and a sheet carrier concentration of $\sim 5 \cdot 10^{15} \text{ m}^{-2}$. No parallel conduction is present in these heterostructures (as evidenced by a vanishing of the resistivity component ρ_{xx} under quantum-Hall conditions), and only one

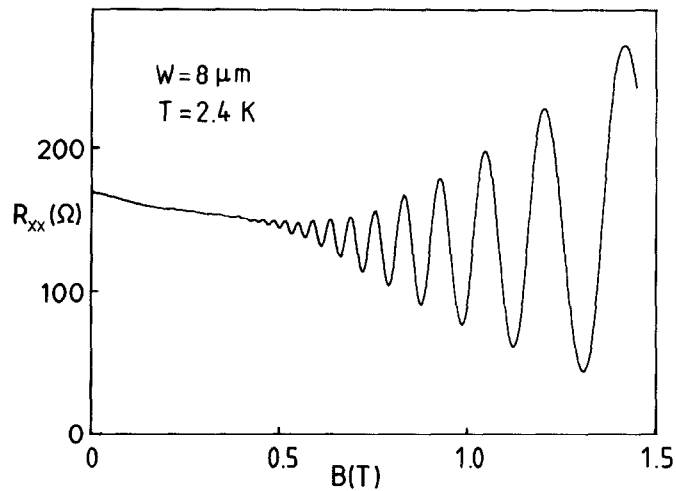


fig. 1 Oscillatory magnetoresistance in a $8.0 \mu\text{m}$ wide GaAs-AlGaAs heterostructure at 2.4 K.

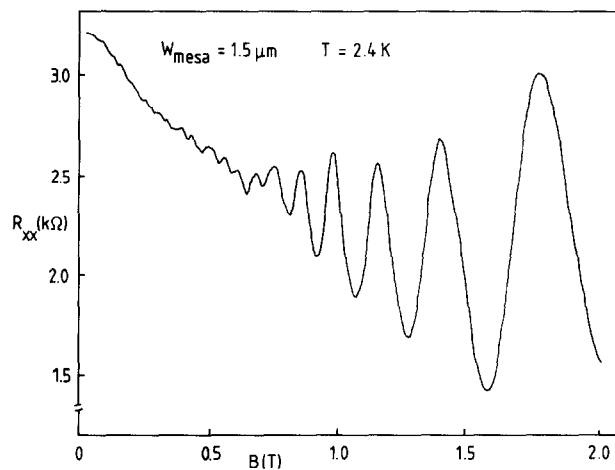


fig. 2 Oscillatory magnetoresistance for the $1.5 \mu\text{m}$ nominal width sample at 2.4 K. Reproducible struc-

ture at low fields is attributed to universal conductance fluctuations.

2-dimensional electric subband is occupied. The samples consist of $10 \mu\text{m}$ long narrow channels connected to broad 2-DEG regions provided with two ohmic contacts each. As a consequence of side wall depletion the effective width W of the samples is lower than the width of the etched mesa ($W_{\text{mesa}} = 0.5, 1.5$ and $8 \mu\text{m}$). From an analysis of the weak field negative magnetoresistance in terms of a theory for weak localization in the presence of boundary scattering¹¹ we recently found that the effective width of the $0.5 \mu\text{m}$ wide sample is a factor of 5 smaller. Similar large sidewall depletion effects have been observed by Choi *et al.*¹². The relative decrease of the

width will be less for the wider channels, but can still be appreciable in the case of the $1.5 \mu\text{m}$ wide channel. As shown below, the subband depopulation data presented in this paper provide an alternative way to get information concerning the effective channel width.

In Figs. 1, 2 and 3 typical magnetoresistance traces are shown for the three samples studied at a temperature of 2.4 K. In sufficiently high magnetic fields (depending on the sample width) Shubnikov-de Haas (SdH) oscillations appear in the magnetoresistance. These oscillations are caused by density of states peaks associated with Landau level quantization of

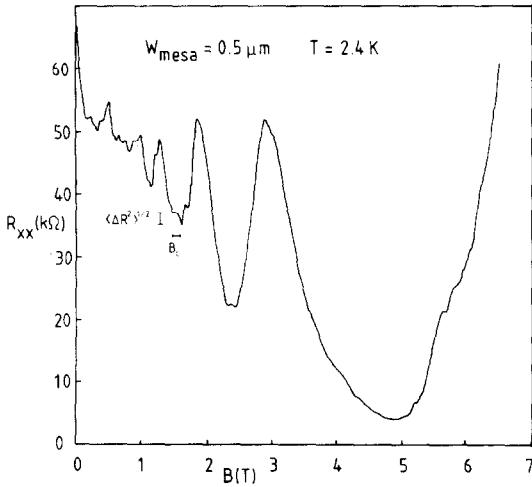


fig. 3 Oscillatory magnetoresistance for the 0.5 μm nominal width sample at 2.4 K. Reproducible structure at low fields is attributed to universal conductance fluctuations (typical field scale and amplitude predicted by theory are indicated).

the 2-DEG. From a (straight line) plot of the Landau level index N_L as a function of B^{-1} the sheet carrier concentration n_s can be obtained according to

$$N_L = n_s \frac{\pi \hbar}{eB} \quad [1]$$

The data for the 8 μm wide sample indeed show this

linear dependence (see Fig. 4), and the resulting sheet carrier concentration is $4.0 \cdot 10^{15} \text{ m}^{-2}$. For the samples with $W_{\text{mesa}} = 1.5$ and $0.5 \mu\text{m}$ the oscillations resemble Shubnikov-De Haas oscillations at higher fields only. The corresponding plots of Landau level index versus B^{-1} in Fig. 4 show clear deviations from a linear dependence below a critical field which depends on the channel width. The data in Fig. 4 thus provide convincing evidence for a transition to the regime of depopulation of 1-dimensional subbands^{4,7}. An estimate of the critical field for this transition can be obtained in the following way. Deviations from pure SdH oscillations are expected to appear if the cyclotron orbit diameter d becomes larger than the channel width W . This diameter is given by

$$d = 2 \left(\frac{\hbar(2N_L + 1)}{m^* \omega_c} \right)^{1/2} \quad [2]$$

with $\omega_c = eB/m^*$ the cyclotron frequency and m^* the electron effective mass. Thus, we can estimate the critical field if the channel width is known, or *vice versa* we can determine the width from the critical field. We shall illustrate this for our 0.5 μm nominal width sample where we find deviations from a straight line (see fig. 4) beyond $B^{-1} \sim 0.6 \text{ T}^{-1}$, at a Landau level index $N_L = 3$. From $d_c = W$ we find $W = 110 \text{ nm}$, with an estimated uncertainty of 20 %. This value agrees very well with the effective width (106 nm) found from our analysis of the weak field magnetoresistance¹¹. At sufficiently high magnetic fields, where $d_c \ll W$, the electron states will approach

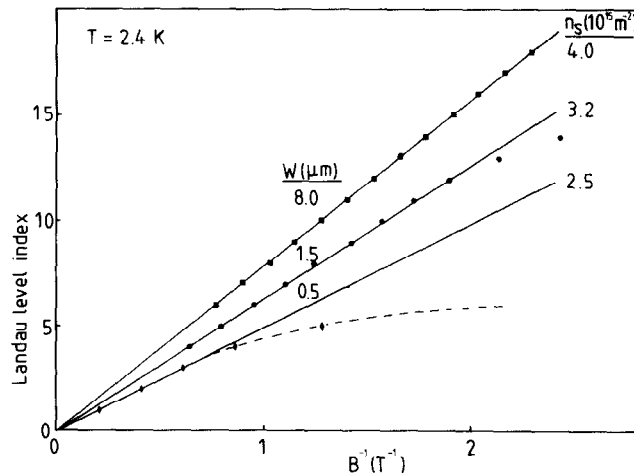


fig. 4 Plot of Landau level index versus B^{-1} for the magnetoresistance traces from figs. 1, 2 and 3. Deviations from a straight line indicate subband depopulation effects. Sheet carrier concentration n_s is

calculated from the high field behavior according to eq. (1). The dashed line represents a fit of the parabolic confinement model.

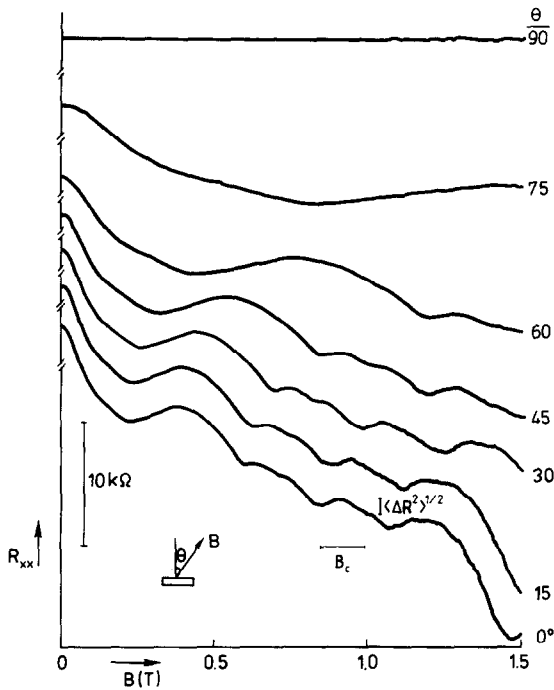


fig. 5 Angular dependence of magnetoresistance for the 0.5 μm nominal width sample at 4.0 K. Curves have been offset vertically for clarity (typical field scale and magnitude of the universal conductance fluctuations predicted by theory are indicated).

pure Landau levels, and therefore it is expected that, if the channel is not too narrow, the sheet carrier concentration can be estimated from the high field slope of the Landau level index plot according to eq. (1). The sheet carrier concentration thus obtained for the narrowest channel is $2.5 \times 10^{15} \text{ m}^{-2}$. Similarly, we find for the 1.5 μm nominal width sample $n_s = 3.2 \times 10^{15} \text{ m}^{-2}$. From $d_c = W$ we find for this sample $W = 350 \text{ nm}$, which is rather lower than we would expect. Unfortunately, we do not have a reliable value for the width from weak field magnetoresistance measurements for this sample to compare with.

A more sophisticated analysis is possible if a model potential is assumed for the lateral confinement of the electrons. We analyzed our data using a simple parabolic confinement potential, which has the advantage that the subband structure in a magnetic field can be solved analytically^{5,7}. While for our narrowest sample this potential may be a reasonable approximation, for the wider channels⁵ it is not to be expected that this potential is adequate. Details of the model and the fit procedure used will be published elsewhere. Two unknown parameters occur in the model: the carrier density per unit length N_e and the characteristic frequency of the parabolic confining potential ω_0 . These parameters can be determined from a fit to the subband depopulation data. As

shown in Fig. 4 (dashed line), the fit of this model for the narrowest channel is quite good. It follows from the analysis that 5 one-dimensional subbands are occupied in this channel. The parameter values found are $\omega_0 = 2.31 \times 10^{12} \text{ s}^{-1}$ and $N_e = 4.27 \times 10^8 \text{ m}^{-1}$. For comparison with the earlier estimates, it is useful to transform these values to the quantities channel width and sheet carrier concentration. An effective width W^{par} can be defined for the parabolic potential according to

$$W^{\text{par}} = 2\pi N_e^{1/3} \left(\frac{3\pi}{2} \frac{m^*}{h} \omega_0 \right)^{-2/3} \quad [3]$$

This is essentially the width between the classical turning points at the Fermi energy in the many subband limit. The average sheet carrier concentration simply follows from $n_s = N_e / W^{\text{par}}$. According to eq. (3) we find $W^{\text{par}} = 138 \text{ nm}$ and thus $n_s = 3 \times 10^{15} \text{ m}^{-2}$, which is consistent with the earlier estimate, and with the results from the weak field magnetoresistance¹¹ given above. As expected, for the 1.5 μm wide channel the parabolic model did not fit the data very well, so that the resulting parameter values are not reliable. For this wider channel the parabolic model is too unrealistic. A potential model with a flat middle section and parabolic walls would probably be a better approximation in this case⁵, but such a model contains an additional unknown parameter. In this paper we therefore only present the results of the analysis of the subband depopulation data for our narrowest sample.

The small width and the decreased carrier concentration for the narrow channel is attributed to sidewall depletion. Due to the 2-dimensional nature of the electrostatic problem, simple estimates for the depletion length are inadequate. It would be interesting to determine the realistic potential for our structure from a self-consistent solution of the Poisson and Schrödinger equations¹³. However, the presence of damage related traps and deep levels in the semiconductor material is likely to complicate such a calculation.

We now turn to the irregular structure observed in the magnetoresistance of the 0.5 and 1.5 μm wide channels at lower fields (see figs. 2 and 3). This structure cannot solely be attributed to density of states peaks associated with the 1-dimensional subbands. The structure is reproducible if the sample is maintained at low temperatures, and it is symmetric in the applied field¹⁰. In order to get further information we measured the angular dependence of the transverse magnetoresistance at 4.0 K. In fig. 5 the results are shown for the 0.5 μm nominal width sample. For fields parallel to the GaAs-AlGaAs interface the magnetic field effect vanishes. Moreover, we found a linear dependence of the B^{-1} values of various maxima and minima on $\cos \theta$ (not shown). The observed effects are thus caused by the perpendicular component of the magnetic field only. Consequently, the effects arise exclusively from the 2-dimensional

orbital motion of the electrons, and spin effects are irrelevant in this field range. (An analogous study of the 3-dimensional magnetoresistance in doped GaAs wires has been performed by Whittington *et al.*¹⁴). The field orientation dependence thus supports an interpretation of the aperiodic oscillations in terms of universal conductance fluctuations. The UCF theory^{8,9} predicts a typical magnitude of the conductance fluctuations (see also ref. 15).

$$\langle \Delta G^2 \rangle^{1/2} \sim \frac{e^2}{h} \sqrt{\frac{l_t^2 l_\phi}{L^3}} \quad [4]$$

and a typical field scale given by $B_c = \sqrt{3} h/eWl_\phi$. These expressions apply if the electron phase coherence length l_ϕ and the thermal diffusion length $l_t = \sqrt{\hbar D/kT}$ are both smaller than the sample length L and larger than the width W . This is the case for our 0.5 μm sample which, as stated above, has an effective width of 110 nm. From the weak field magnetoresistance analysis¹¹ we found a diffusion constant $D = 0.039 \text{ m}^2 \text{ s}^{-1}$ and $l_\phi = 450 \text{ nm}$ at 4.0 K and 600 nm at 2.4 K. In Figs. 3 and 5 the resulting values for B_c and $\langle \Delta R^2 \rangle^{1/2} \sim R^2 \langle \Delta G^2 \rangle^{1/2}$ are indicated, showing good agreement with the experimental data. (In fig. 3 part of the larger structure at low fields may still be caused by magnetic depopulation of subbands, rather than the UCF effect). As expected from the theory the oscillations in the 1.5 μm wide channel are smaller and they occur on a smaller typical field scale, as a consequence of the larger width. We note that because of the high mobility the elastic mean free path is larger than the sample width so that boundary scattering effects may influence the universal conductance fluctuations in these structures. We recently discussed the influence of boundary scattering for the related problem of weak localization in these structures, and showed that the sidewall scattering is specular rather than diffuse¹¹.

In conclusion we have presented high field oscillatory magnetoresistance data for narrow channel GaAs-AlGaAs heterostructures which provides clear evidence for both subband depopulation effects and universal conductance fluctuations.

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